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Review of small hydropower technology

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ABSTRACT

This paper gives a review of small hydropower technology. A Small hydropower (SHP) plant uses impulse or reaction turbines and is mainly 'run-off-river'. SHP technologies currently used in generating electricity for rural electrification in both developed and underdeveloped countries are helping to slow down climatic change, creating employment opportunities, and are having low maintenance costs (but high capital costs).

Contents

1. Introduction

Energy resources are grouped into three categories: fossil fuels, renewable resources and nuclear resources. Renewable energy resources can be used to produce energy again and again, e.g. hydropower, solar energy, wind energy, biomass energy, geothermal energy, etc. [1]. Hydropower currently represents worldwide a significant source of electrical energy and compared to fossil and nuclear fuel, hydro resources are widely distributed [2]. It contributes to one-fifth of the total power worldwide and in many countries it is the only domestic source for electricity generation [3]. The 1997 report on survey by the International Journal on Hydropower and Dams indicated that at least 50% and 90% of the national electricity in 63 and 23 countries respectively are sourced from hydro [2]. The role hydro resource is playing in generating electricity is substantially greater than that of any other renewable energy technology and vast potential still remains in underdeveloped countries [3]. Hydropower project exists in a wide range of scale as well as types and the design is made to suit the needs and conditions at a particular site [3]. Small, mini and micro-hydro plants play a key role of rural electrification in many countries [2,5] and they have greater capacity than all other renewable energy sources to make instant impact on the replacement of fossil fuels.

2. Small Hydro

Hydropower plants are of three types [4]:

- Impoundment: this is a large hydropower system which uses a dam to store river water in reservoir. Water stored in the reservoir is then used to generate electricity.
- Diversion: a diversion facility channels a portion of a river through a canal or penstock. This system may not require the use of a dam.
- Run-of-river: the system uses water within the natural flow range and it requires little or no impoundment.

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In the 20th century, the development of hydroelectric power involved the building of large dams. Huge artificial lakes were created by placing massive barriers of concrete, rock and earth across river valleys [2,5]. “While they created a major reliable power supply plus irrigation and flood control benefits, the dams necessarily flooded large areas of fertile land and displaced many thousands of local inhabitants” [2,5]. The rapid silting up of the dam reduces its productivity and lifetime. In addition, such major interference with river flows can lead to several environmental problems [2,5]. Table 2.1 gives detailed information on the strengths and weaknesses of hydropower.

Small-scale hydro is mainly ‘run of river,’ so it involves construction of a quite small dam or barrage, usually just a weir, and generally little or no water is stored [7]. Civil works regulate the water level at the intake to the power-plant [7]. In low (5 m < head < 15 m) or medium (head > 15 m) installations, a canal carries the water to the forebay/settling tank. Generally for low-head installations (head < 5 m), water enters the turbine almost directly from the weir [2,5]. The size of a small hydropower scheme is about 10 MW or less, although, most countries define the scheme differently.

2.1. Small hydro site characteristics

Fig. 2.1 illustrates a typical run-of-river small hydro scheme. The fundamental elements are the weir, the settling tank (the forebay), the penstock and a small canal or “leat” [8]. Water is diverted from the course (main river) through an intake at the weir. The weir is a man-made barrier across the river which regulates the water flow through the intake [7]. Before entering the turbine, the particulate matter is removed by passing water through a settling tank. Water is sufficiently slowed down in the settling tank for the particulate matter to settle out. A protective rack of metal bars (trash rack) is typically found near the forebay to protect the turbines from damage by larger materials such as stones, timber, leaves and man-made litter that may be found in the stream [7].

A pressure pipe, called penstock, conveys the water from the forebay to the turbine [7,8]. All installations require a valve (sluice gate) at the top of the penstock which can be closed when the turbine is to be shut down and emptied of water for maintenance. When the sluice gate is closed, a canal known as the spillway is used to divert water back to the river [7].

The head is the vertical distance that water falls. It may be influenced by the characteristics of the channel or pipe through which the water flows [9,10]. It is usually measured in metres or units of pressure. “Most small hydropower sites are categorised as low or high head” [9,10]. In the determination of head, both the gross head (i.e. the vertical distance between the top of the penstock that conveys the water under pressure and the point where the water discharges from the turbine) and net head are considered [10]. Net head (H) is the difference between gross head

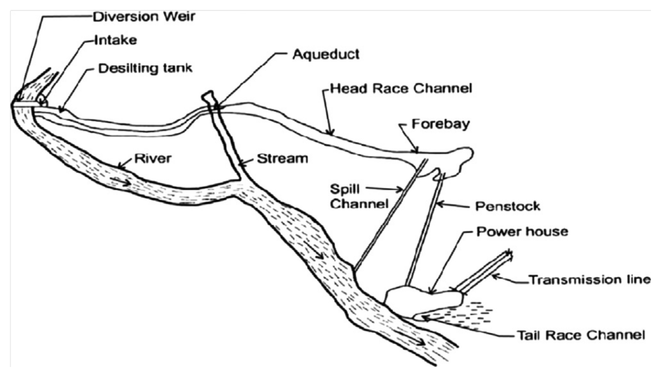

Fig 2.1. Typical small hydro site layout [8]. (Singal S.K., Saini R.P. and Raghuvanshi C. S. (2010). Analysis for cost estimation of low head run-of-river small hydropower schemes. *Energy for Sustainable Development 14, 117–126*).

Table 2.1
Advantages and disadvantages of hydropower option.

Advantages	Disadvantages
Economic aspects	
• Has low operating and maintenance costs [3,5]. • It is a long-lasting and robust technology; systems can last for 50–100 years or more without major new investments [3,5]. • A reliable source of energy [3,5]. • Includes proven technology [3,5]. • Promotes regional development [5]. • Technology with highest efficiency [3,5]. • Generates revenues to sustain other water [3]. • Creates employment opportunities and saves fuel [3,5].	• High capital cost [3,5]. • Requires multidisciplinary involvement [5]. • Precipitation [3,5]. • Long-term planning is required [3,5]. • Long-term agreement is required [3,5]. • Requires out sourcing of contractors and funding [3,5].
Social aspects	
• Improves standard of living [3,5]. • Leaves water available for other uses [5]. • Frequently provide flood protection [3,5]. • May enhance navigation conditions [5]. • Enhances recreation [3,5]. • Enhances accessibility of the territory and its resources [3,5].	• May lead to resettlement [3,5]. • Limits navigation [3,5]. • Damming of large area reduce public access to some areas. This affects outdoor recreation activities [6]. • Requires checking of waterborne disease vectors [3,5]. • The power lines can change the land scape [6]. • Management of competing water uses is needed [3,5].
Environmental aspects	
• Produces no atmospheric pollutant and only very few GHG emissions [3,5,6]. • No waste is produced [3,5]. • Avoids depleting non-renewable fuel resources [3,5]. • Creates new freshwater ecosystems with increased productivity [3,5]. • Enhances skill development [3,5]. • Slow down climate change [3,5].	• Barriers for fish migration and fish entrainment. • Involve modification of aquatic habitats [3,5]. • Requires management of water quality [5]. • The methyl mercury introduction into the food chain requires close monitoring/management [3,5]. • The populations may need to be monitored [3,5]. • Damming areas rich in biodiverse flora results in carbon emissions [6].

(H_g) and losses due to friction, turbulences in the piping (ΔH_{AB}) [9,10] and the energy required for the water to exit the plant.

$$H = H_g - \Delta H_{AB} \quad (2.1)$$

Small hydro systems with a change in elevation of less than 5 m are referred to as low head systems. However, if the vertical drop is less than 2 m, a small-scale hydroelectric system will probably be unfeasible. A plant with a higher head requires less flow than a low head plant in order to generate the same amount of electricity [10].

2.2. The principles of small hydropower

Fig. 2.2 shows components of a hydropower scheme. "The basic hydropower principle is based on the conversion of a large part of the gross head, $H_g(m)$ (i.e. net head, $H(m)$) into mechanical and electrical energy" [9]. Figs. 2.3, 2.5, 2.6 and 2.7 show respectively typical Pelton, propeller, Francis and Archimedes screw turbine.

Water pressure is converted by hydro turbines into mechanical shaft power. The mechanical shaft power can be used to drive an electrical generator or other machinery [2]. The available power is directly proportional to the product of pressure head and volume flow rate [2,8]. Generally, the hydraulic power $P_0(kW)$ and the corresponding energy $E_0(kWh)$ over an interval of time $\Delta t(h)$ are [9]

$$P_0 = \rho g Q H \quad (2.2)$$

$$E_0 = \rho g Q H \, \Delta t \quad (2.3)$$

where ρ and g are the density of water (kgm^{-3}) and acceleration due to gravity (ms^{-2}) respectively. The final power, P delivered to the network is smaller than P_0. The power output of any hydropower plant is given by:

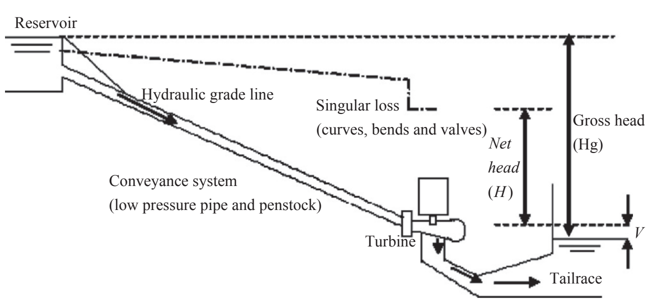

Fig. 2.2. Components of a hydropower scheme [9].

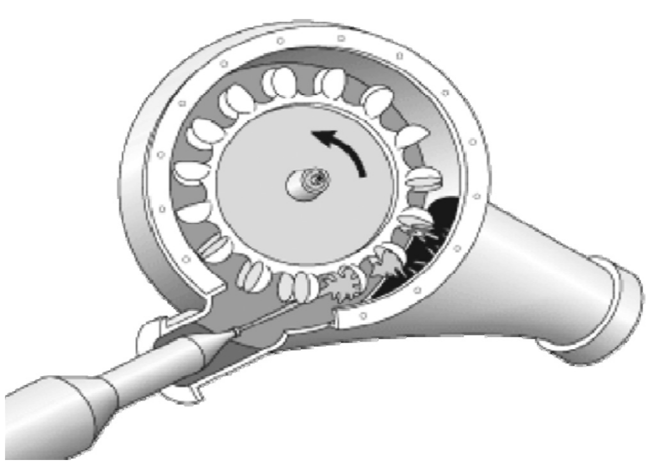

Fig. 2.3. Typical Pelton turbine [11]. (Southeast Power Engineering Ltd Website: http://sepengineering.com/. Accessed on May 26, 2013).

$$P = \eta P_0 \quad (2.4)$$

where η is the hydraulic efficiency of the turbo-generator.

Hydro is still the most efficient way to generate electricity. Modern hydro turbines are capable of converting up to 90% of the available energy into electricity, [2,7] although this reduces with size [7]. Micro-hydro systems tend to be in the range of 60–80% efficiency [7].

2.3. Types of hydropower turbines

Turbines used in hydroelectric systems have runners of different shapes and sizes [11]. There are two main categories of hydro turbines in use: impulse and reaction turbines. The selection of any type of hydropower turbine for a project is based on the head and the flow or volume of water at the site. However, other deciding factors include how deep the turbine must be set, efficiency and cost [4].

Impulse Turbine: the impulse turbine uses the kinetic energy of water to drive the runner and discharges to atmospheric pressure [4]. The runner of impulse turbines operates in air and is moved by jets of water; "the water remains at atmospheric pressure before and after making contact with the runner blades" [8]. Water that falls into the tail water after striking the buckets has little energy remaining, thus the turbine has light casing that serves the purpose of preventing the surroundings against water splashing [12]. An impulse turbine is usually applied in systems with high head and low flow. There are three common types of impulse turbines: the Pelton, the Cross-flow and Turgo [4].

- **Pelton:** this form of turbine has a wheel containing a series of split buckets (vanes) set around its rim. A jet of high pressure water is directed tangentially at the wheel thereby hitting each bucket individually. The jet is split in half and each half is turned and deflected back almost through 180° [8]. The jets are issued through nozzles, each with an axis in the plane of the runner and a needle (or spear) valve to control the flow. To stop the turbine, in case the turbine approaches the runaway speed due to load rejection, the jet is deflected by a plate so that it does not impinge on the buckets. In this way the needle valve is closed very slowly thus keeping the overpressure surge in the pipeline to an acceptable minimum. The kinetic energy of water leaving the runner is lost and so the buckets are designed to keep exit velocities to a minimum [12]. This turbine does not require draft tubes since the runner are positioned above the maximum tail water to permit operation at atmospheric pressure [4]. Pelton turbines are usually applied in systems with large water heads [11]. Fig. 2.4 shows the head-flow

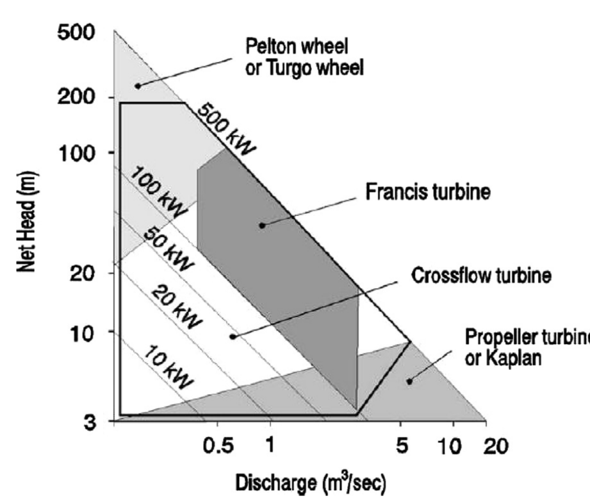

Fig. 2.4. Head-flow ranges of small hydro turbines [8].

ranges of different small hydro turbines. Unlike the Francis turbine, Pelton and cross flow turbines can operate at high efficiencies even when running below their design flow.

- **Cross-flow:** the cross flow (or Banki) turbine has a drum-like rotor and uses an elongated, rectangular-section nozzle which is directed against curved vanes on a cylindrically shaped runner [4]. Cross-flow turbines are less efficient than the modern-day turbines (i.e. Pelton, Turgo, Francis and Kaplan), but it can accommodate larger water flows and lower heads [12]. A jet of water enters the turbine, thus gets directed through the guide-vanes at a transition piece upstream on the runner which is built from two or more parallel disks connected near their rims by a series of curved blades. The flow is directed to a limited portion of the runner by the guide vane at the entrance to the turbine [4]. The turbine allows water to flow twice through the blades. In the first stage water flows from the outside of the blades to the inside; in the second stage the water passes from the inside back out. The flow leaves the first stage attempts to cross the open centre of the turbine but as the flow enters the second stage, a compromise direction is achieved which causes significant shock losses [4,8,12].
- **Turgo:** this turbine is similar to the Pelton, but with different shape of the buckets [12] and the jet strikes the plane of the runner at an angle (typically 20°) [8,12]. The jet of water enters the runner through one side and exits through the other side. Unlike a Pelton turbine, the flow rate through a Turgo turbine is not limited by the discharged fluid interfering with the incoming jet [8,12]. Consequently, a Turgo turbine can have a smaller diameter runner compared to that of a Pelton turbine with an equivalent power output [8]. A Turgo turbine has a higher running speed which makes a direct coupling of turbine and generator more likely, thus increasing the overall efficiency and decreasing maintenance [12]. Turgo turbines operate effectively in systems with large water heads (see Fig. 2.4).

Reaction turbine: this turbine generates electricity from the mutual action of pressure and by moving water [4]. The reaction turbine operates when the rotor is fully submerged in water and is enclosed in a pressure casing. "The runner blades are profiled so that pressure differences across them impose lift forces, akin to those on aircraft wings, which cause the runner to rotate". [8]. Reaction turbines are generally appropriate for sites with lower head and higher flows compared with the impulse turbines [4]. Typical Reaction turbine types are Propeller, Francis and Kinetic. Figs. 2.5–2.7.

- **Propeller:** a propeller turbine generally has an axial flow runner with three to six blades depending on the designed water head. For higher efficiency the water needs to be given some swirl before entering the turbine runner [4,8,11]. Propeller turbines are suitable for systems with low water heads [11,13]. There are several different types of propeller turbines: bulb turbine, Kaplan, Straflo and tube turbine [8]. "The Kaplan turbine has adjustable blade pitch and it can achieve high efficiency under varying power output conditions" [11]. The methods used for adding inlet swirl include fixed guide vanes mounted upstream of the runner and a "snail shell" housing for the runner, in which the water enters tangentially and is forced to spiral in to the runner. In the case of the Kaplan turbine, the blades of the runner are adjusted. Adjustment of the turbine blades and guide vanes can greatly improve efficiency over a wide range of flows; however it is costly and so can only be economical in larger systems [8]. The unregulated propeller turbines are commonly used in micro-hydro systems where both the flow and head remain practically constant [12].
- **Francis:** this is the most common type of hydropower turbine in use [1]. This turbine generally has radial or mixed radial/axial flow runner which is most commonly mounted in a spiral casing with internal adjustable guide vanes. Water flows radially inwards into the runner and emerges axially, causing it to spin. In addition to the runner, the other major components include the wicket gates and draft tube [4,8]. The runners with smaller diameter are made of aluminium bronze casting, while the larger runners are fabricated from curved stainless steel plates that are welded to cast steel hub [12]. Francis turbines are applied in hydroelectric systems with medium head size and their efficiency can be above 90% [11] but tend to

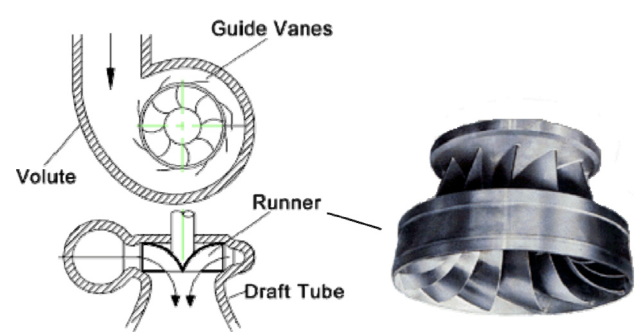

Fig. 2.6. Typical Francis turbine [11]. (Southeast Power Engineering Ltd Website: http://sepengineering.com/. Accessed on May 26, 2013).

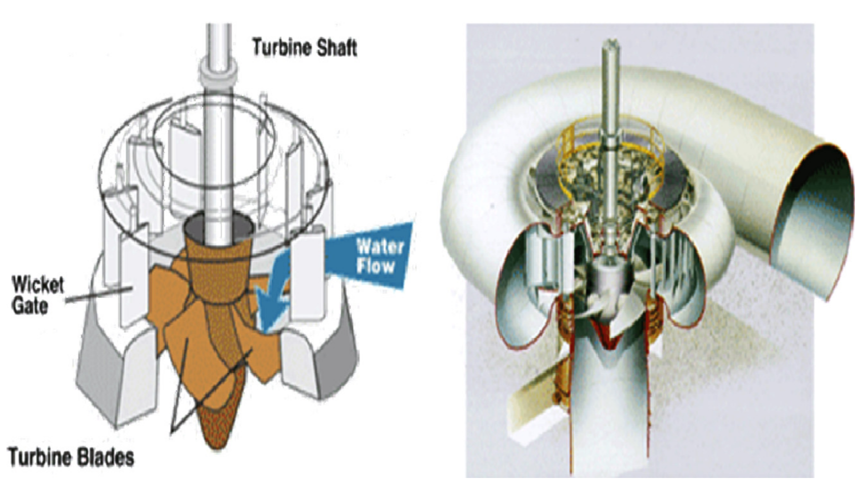

Fig. 2.5. Typical propeller turbine [11]. (Southeast Power Engineering Ltd Website: http://sepengineering.com/. Accessed on May 26, 2013).

Fig. 2.7. Archimedes screw [14].

be less efficient when there is less water available than their designed flow [13]. For smaller heads and power, the turbine is set in an open flume. However, the turbine can also be attached to a penstock and steel spiral casings is used in cases of relatively higher heads [12].

- **Kinetic/ free-flow:** kinetic turbines produce power from the kinetic energy of the flowing water rather than the potential energy from the head [8]. The systems can be used to generate electricity from rivers, man-made channels, tidal waters, or ocean currents. Kinetic systems utilise the water stream's natural pathway, so they do not require diversion of water through manmade channels, riverbeds, or pipes. However, they can be applied in such conduits [4,8].
- **Archimedes screw:** Archimedes screw is manufactured as bespoke installation. The parameter of a specific hydro site determines the length (which increases as the head increases) and diameter (which increases with increase in design flow) of the turbine. Depending on the cost, the choice of design of Archimedes screw for a particular site includes steel trough closed compact and open compact [14]. With an Archimedes screw, water falls through the screw and turns it. The turning screw turns the gear box and the generator so that electricity can be produced [13]. Archimedes screw is excellent for hydroelectric systems with low heads (2–10 m) and large flow. The advantages of the Archimedes screw over the conventional turbines include: lower installation cost compared with the propeller or cross-flow turbines; require very little screening of fish, floating objects and debris which pass through it; low maintenance cost and the water it uses to generate the electricity can be seen unlike almost all the other turbines [13].

2.4. Investment costs

The cost of installing hydro power plants varies from place to place. It depends on the existing infrastructures [13] and the installation capacity. Generally equipment for a low head plant of a given output is higher than that of a higher head plant with the same output [13]. The low output equipment is also costly [15]. Investment cost is divided into direct and indirect costs.

- Direct costs comprise: civil, electro-mechanical equipment and power transmission line costs [16].
  - Civil costs includes the construction and hydro structural costs as well as dam conveyance of water system, penstock structure, a head pond, the forebay, the power house, tailrace structure, the access and any future unpredicted costs [16,17]. No standard cost unit is given to the civil work. The cost varies with sites depending on the topography and the geology, and the construction method applied and the materials used [15].
  - Electro-mechanical costs include costs met on turbines, generators, governors, gates, control systems, a power substation, electrical and mechanical auxiliary equipment, etc. [16,17]. The electro-mechanical equipment cost accounts for about 30–40% of the total small hydropower plant budget [18]. The cost of electo-mechanical equipment can also be determined using the power, P and the net head, H of the small hydro-power plant from Eq. 2.1 [18].

    $$\text{Cost} = aP^{b-1}H^{c}(€/\text{kW}) \tag{2.1}$$

    where, a, b and c are coefficients that depend on the geographical, space or time field where they are being used.
  - Power transmission line costs include costs met in construction of power transmission line for delivery of energy produced from the hydropower plant to power transmission network. This is mainly determined by the location, type of the system inexistence (i.e. overhead or cable system) and the size of the small hydropower plant and how long the transmission line is [16,17].
- Indirect costs are engineering and design (ED), supervision and administration (SA) as well as inflation costs at period of construction [16,17]. However, ED depends on type; size as well as location of the plant site, as SA (i.e. expenditures on land, management, inspection and supervision) it is also calculated as a percentage of the construction cost [16,17]. Generally, the operation and maintenance costs without major replacements are estimated to be between 3–4% of the capital cost [15]. Hydro-power plants have got high capital costs but low maintenance costs [19]. Based on the Austrian shilling, it was derived that for plants with capacities less than 2 MW and having heads lower than 15 m, the total costs of developing hydro-power plant or renovating it can be obtained from Equation 2.2 [19].

$$\text{Total Cost} = C \times \left(\frac{P}{H^{0.3}}\right)^{y} \tag{2.2}$$

where, both y and C are constants, P is the plant capacity, H is the designed head and the total cost is in Austrian shilling.

3. Conclusion

Small Hydropower technology is one of the most common technologies used for electricity generation for rural population in both developed and developing countries. Inclusion of the remains of this resource in the energy mixes could lead to sustainable development. However, further development of this technology

may be limited by the social, political, economic, historical, regulatory and environmental issues.

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